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The dense plasma focus device is one of the few fusion systems that is capable of burning advanced fuels such as D – ^{3}He and p – ^{11}B. A study has been performed and shown that three main requirements must be satisfied to reach breakeven for DPF fusion: a high Ti/Te ration (~ 20), an order of magnitude higher pinch lifetime, and the reflection and absorption if at least 50% Bremsstrahlung radiation. The latter issue is the focus of this report, and a literature search has been performed on laser-driven fusion radiation cavities, multilayer reflectors, and their application to Bremsstrahlung radiation reflection is presented. Additionally, the results found are compared to those assumed in the earlier DPF study bring p-^{11}B.

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An Investigation of Bremsstrahlung Reflection in a Dense Plasma Focus (DPF) Propulsion Device

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Abstract. The dense plasma focus device is one of the few fusion systems that is capable of burning advanced fuels such as D – ^{3}He and p – ^{11}B. An study has been performed and shown that three main requirements must be satisfied to reach breakeven for DPF fusion: a high Ti/Te ration (~ 20), an order of magnitude higher pinch lifetime, and the reflection and absorption if at least 50% Bremsstrahlung radiation. The latter issue is the focus of this report, and a literature search has been performed on laser-driven fusion radiation cavities, multilayer reflectors, and their application to Bremsstrahlung radiation reflection is presented. Additionally, the results found are compared to those assumed in the earlier DPF study bring p-^{11}B.

Keywords: Magnetic Fusion Propulsion, Bremsstrahlung Reflection.
PACS: 85.70.Rp, 52.25.Os.

INTRODUCTION

Simplicity of design and of engineering characteristics, high yield of nuclear fusion reactions, including neutron-lean fusion reactions with advanced fuels (such as ^{3}He and ^{11}B) qualify dense plasma focus machines as outstanding potential thrusters for space propulsion (Nardi, 1992). In the dense plasma focus concept, fuel is injected into a set of coaxial electrodes, which are connected to a capacitor bank. The capacitor bank is then discharged across the electrodes ionizing gas and forming a plasma sheath. A radial current is induced and the Lorentz force accelerates the plasma sheath down the length of the anode. When the sheath reaches the end of the anode, the collapsing sheath focuses towards the central anode and "pinches" forming a plasma where fusion reactions take place. A schematic view of a Mather-type plasma focus is shown in figure 1.

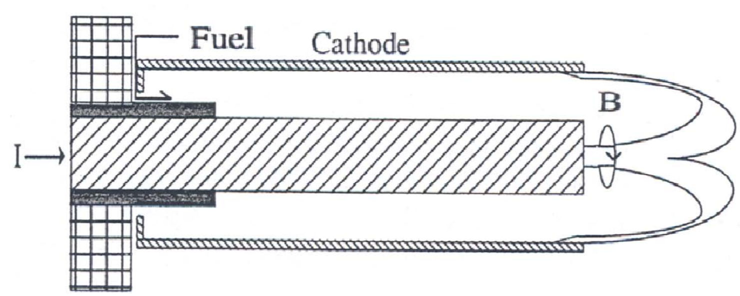

FIGURE 1. A Typical Plasma Focus.

The purpose of this report is to investigate the reflection physics for the high-energy Bremsstrahlung radiation emission characterized in p-^{11}B DPF fusion. A literature search has been performed on Hohlraum cavities,

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multilayer reflectors, and several cooling techniques and will be presented. Fortunately, most of the numerical studies done at Sandia National Laboratory on Hohlraums are directly applicable to our case. The survey of the multilayer research shows that photon energy levels of DPF interest have not yet been investigated (Windt, 2004), however the general trend is towards high energy reflection, and basic analytical models are produced. The vast majority of chamber cooling work that has been done concentrates on the transport mechanism of convection, and ignores radiation. This obviously is not valid in our case; however the basic analytical relations are offered to give insight into the areas needed to be investigated for successful cooling. Also the mass flow rate is estimated which will give an idea of how much extra propellant needs to be carried. Finally, the results found here are compared to those assumed in the earlier DPF investigation burning p-^{11}B (Thomas, 2005).

BREMSSTRAHLUNG RADIATION

Bremsstrahlung radiation, which is German for "braking radiation", occurs when charged particles are decelerated by collisions with other charged particles and emit a photon. This form of radiation is pervasive in high temperature plasmas of fusion interest and constitutes an energy loss and cooling mechanism for the plasma. The problem of Bremsstrahlung emission is amplified in our case because of the high temperatures achieved by the p-^{11}B dense plasma focus (DPF) pinch (~ MeV), and the radiation's Z^2 dependence. To see the importance of Bremsstrahlung reflection consider figure 1.

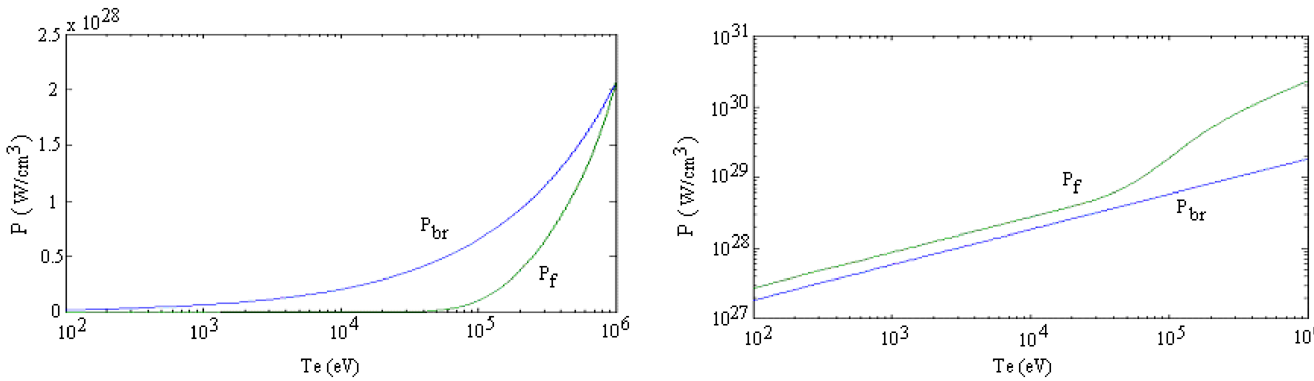

FIGURE 2. Bremsstrahlung Power Density Losses.

For a p-^{11}B fusion reaction essentially in thermodynamic equilibrium, the radiation losses will be large due to the high atomic number of boron. The bremsstrahlung radiation losses will dominate over the fusion heating power as depicted in figure 1(a) and the time change rate of the plasma temperature would be too low to acquire net power output. There are three possible ways to limit the bremsstrahlung losses for DPF devices and get a net power output, one of which is the reflection of Bremsstrahlung radiation. A reflection rate of 60% is assumed in the estimation. figure 1(b) shows bremsstrahlung radiation losses and fusion heating power as a function of Te under the assumption that 60% of the radiation is reflected into the core of the DPF and absorbed by the plasma.

The underlying physics depend on the energy and flux of the incoming radiation to the wall. If the incoming angles and fluxes are small, then multilayer structures would provide the best option for reflection since both hard and soft x-rays have been detected in experiments. If the fluxes and wall temperatures reach high enough levels (>10^5 K) then a plasma will be created at a wall, and numerical radiative hydrodynamic analysis is necessary to find the reemission of the photons. Both cases will be presented here, beginning with an estimation of the flux, temperature, and ablation at the wall using classical heat transfer relations.

In order to correctly ascertain the relevant reflection physics it is first necessary to define the incoming energy and power flux to the wall. The total Bremsstrahlung power density is estimated by:

$$P_{tot} = 5.35 \times 10^{-37} Z_{eff} n_e^2 (kT_e)^2 . \tag{1}$$

Where Z_{eff} has a value of 13 for the p-^{11}B reaction. The radiation energy after each pulse is found by:

$$E_{br} = \tau_p P_{tot} V_{pin} \, . \tag{2}$$

The power deposited to the wall is found by multiplying the energy with the repetition rate ν:

$$P_{br} = E_{br} \nu \; . \tag{3}$$

Using the values found from the DPF study (1) for a 500 kN propulsion unit, an energy and power flux of 1.23×10^5 J/cm^2 and 1.26×10^6 W/cm^2 are found, respectively. These values will be used for the rest of the report.

WALL HEATING AND EVAPORATION

In this section the evaporation rate and wall temperature will be has been estimated using classical heat transfer. Once an estimation of these parameters is found, a more accurate analysis can be obtained. The analysis completed followed the work done by Kammash (1975), who formulated the problem under conditions of thermonuclear interest. The rate of evaporation can be estimated from the vapor pressure of the solid material above the surface and is given by Kammash (1975):

$$\frac{dn}{dt} = \frac{3.5 \times 10^{22}}{\sqrt{M}} \frac{P(T)\,[\text{Torr}]}{\sqrt{T}\ (\text{K})} \, . \tag{4}$$

The most severe thermal loading on the wall occurs when the plasma is at the end of a discharge and the plasma is "dumped" on the wall in a very shot period of time. The wall temperature as a function of wall "dumping" time is shown in Figure 2, for various DPF thrust levels.

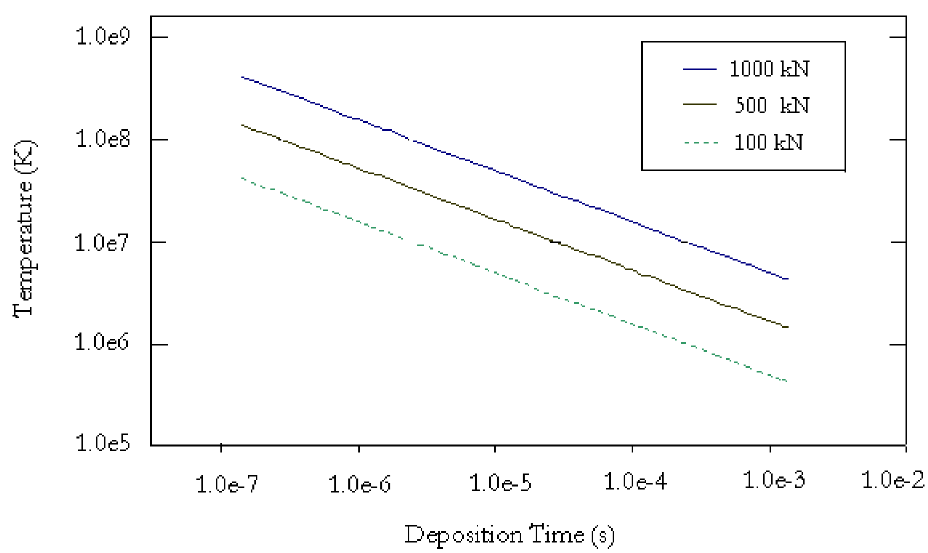

FIGURE 3. Log Scale of Temperature vs. Deposition Time.

The thickness of ablated material per pulse is found through the use of:

$$n = 0.2\tau \frac{dn}{dt}(T_{\max}) \, . \tag{5}$$

Where the dn/dt term is the time rate change in atoms evaluated at T_{max} and τ is the deposition time. The number of pulses shown goes up to roughly 8.5×10^5 pulses, which is how many times it would fire if it ran at a repetition rate of 10 Hz continuously for one day.

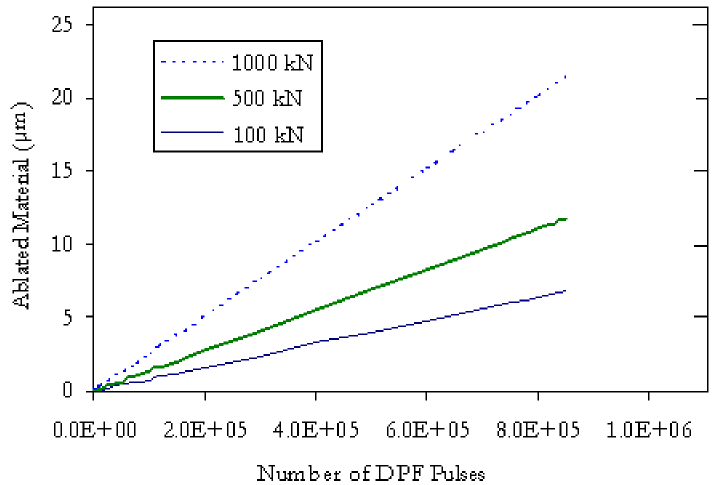

FIGURE 4. Ablated Material as a Function of DPF Pulses.

It can be seen the temperatures reach above the10^5 K, and when the temperature of the wall begins to exceed this value, the wall will itself become an intense radiator and eventually determine the radiation field in the cavity. The requisite physics have been studied in the use of Hohlraums, which is discussed in the following section.

X-RAY CONFINEMENT PHYSICS

The investigation of x-ray confinement in fusion systems has been driven by research on the use of Hohlraums in Inertial Confinement Fusion (ICF). In ICF, small, spherical fuel pellets are imploded by high-power lasers or ion beams. In order to achieve symmetric compression, the pellets can be placed in cylindrical gold-plated cavities called Hohlraums. The Hohlraum contains small holes through which beams pass, and when targeted by a laser or ions, the Hohlraum converts the beam into soft x-rays on the inner wall which subsequently provide indirect heating of the total inner wall. The confinement effect arises because the cavity wall heats up due to the heating from this source and becomes itself a strong emitter of thermal soft x-ray radiation (5). In this way a fraction of the flux which the wall receives from the source is reemitted from the cavity. A diagram of ICF concept utilizing a Hohlraum is illustrated in Figure 4 (Haan, 2005).

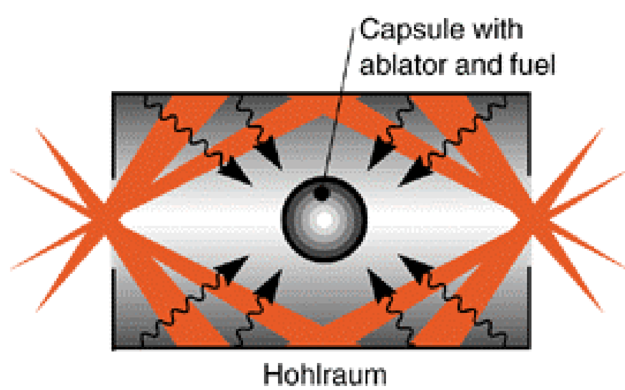

FIGURE 5. Indirect Drive ICF Concept.

Thus far, ignition experiments have used indirect drives in which an external laser light heats the cavity the Hohlraum cavity. The light is converted with close to 100 percent efficiency into an intense flux of x-rays of almost 1,000 terawatts per square centimeter (Haan, 2005). The x-rays converge on the capsule's outer ablator layer, heating and expanding it. The rocket-like blow off of the ablator then pushes the rest of the capsule inward, compressing the interior fuel to extreme pressures and temperatures.

Numerical Models

Quantitative modeling of the injection of several laser beams into the cavity, the subsequent conversion of the laser light into soft x-rays, and the resulting spatial distribution of energy deposition possess considerable difficulties, owing to the complicated geometry and the rather involved physics of laser light conversion (Nishimura, 1991). In order to reach a more tractable model, the laser is replaced by a fictitious source of x-rays located inside the cavity wall. In our case, this x-ray source is the Bremsstrahlung radiation produced from the DPF device, and the pinch region will serve as the target region as opposed to a frozen D-T pellet.

In the physics model it is also assumed that radiation and matter are in complete thermodynamic equilibrium in the cavity, i.e., the wall emits Plank radiation according to Boltzmann's equation into the cavity and the loss of energy by diffusion into the wall can be calculated by an approximation of radiation heat conduction. The reemission of the x-rays is determined by a nonlinear heat wave which forms on the inside of the wall. A diagram of the wave propagation process is illustrated in Figure 5 (Pakula and Sigel, 1985). At time t = 0 (a) the body is brought into contact with a thermal bath. For t > 0 (b) first a nonlinear heat wave runs into the undisturbed material. Subsequently, hydrodynamic motion of the heated material becomes important, and the heat wave is overtaken by a shock wave and the ablative heat wave forms.

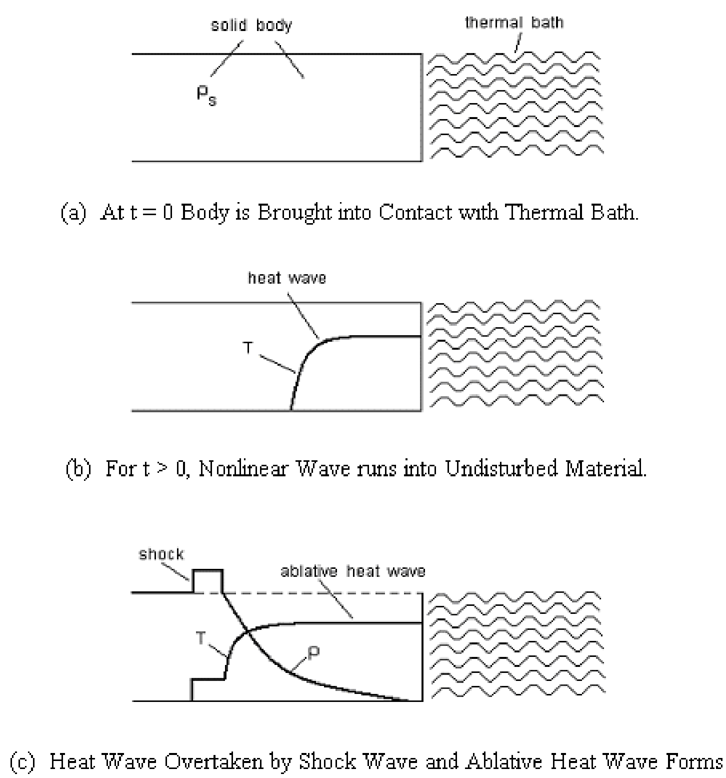

FIGURE 6. Heating of a Solid Body in Contact with a Thermal Bath.

Similarity Analytical Model

There have been varying levels of sophistication in the x-ray reflection models produced, but in general, the following is true. The key parameter for describing radiation confinement in a cavity is the *reemission coefficient* of the x-ray heated wall (5). It is determined by a radiation-driven ablative heat wave propagating into the depth of the wall material as described by Pakula and Sigel (Pakula and Sigel, 1985). To understand the situation, consider the case where a solid gold wall is irradiated from the left with a constant radiation flux as shown in figure 6.

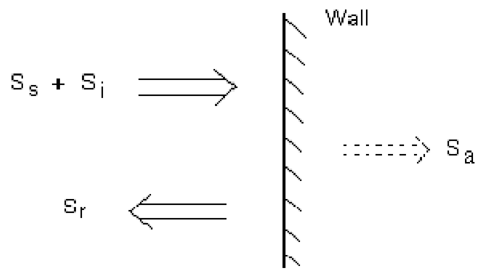

FIGURE 7. Flux at the Interface Between Wall and Inner Cavity.

The wall receives a flux S_s from a source and an incident flux S_i of thermal radiation from the other wall elements in the cavity. The wall radiates a reemitted flux S_r into the cavity whereas a net heat flux S_{hw} of radiation diffuses into the wall, by a process known as photon diffusion. The energy balance of this process is given by:

$$S_s + S_i = S_r + S_a \,. \tag{6}$$

For a completely closed cavity (no holes) the source flux must flow into the wall; there is no other loss than the heat propagation into the wall. More advanced models have been used to estimate the reemitted x-ray flux. Again using an ablative heat wave to model the x-ray flux inside the reflector, Murakami (Murakami, 1991) assumed the coefficient for radiation thermal conductivity is directly related to the radiation mean free path and therefore to the Rosseland mean opacity. For Gold, the reemitted flux is modeled by:

$$S_r = 13.0 S_a^{1.05} t^{0.46} \,. \tag{7}$$

Where the fluxes are in units of 10^{14} W/cm^2 and time is in the units of 10^{-8} s. An important result not shown here from Murakami's analysis is that high Z gold reemits incident radiation ten times more efficiently than low Z-carbon, and vice versa, carbon absorbs ten times more per unit area than gold when in contact with the same radiation field. By using (23) a plot of the reemission coefficient vs. time can be reproduced.

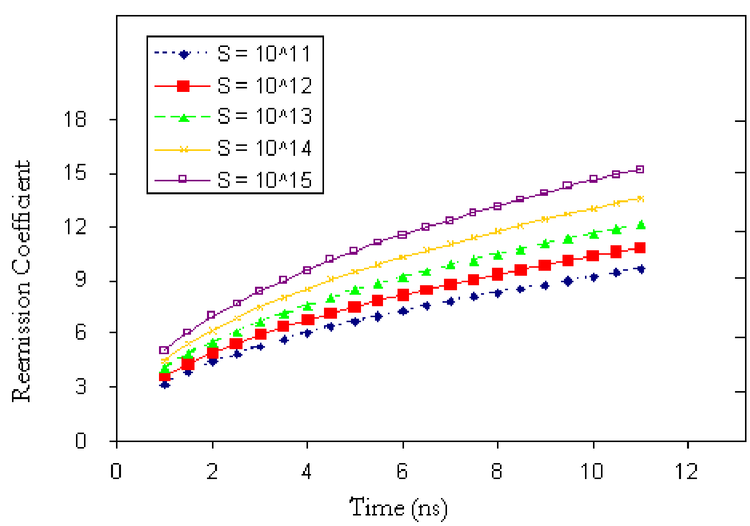

FIGURE 8. Reemission Coefficient vs. Time for Various Bremsstrahlung Fluxes For Gold.

The immediate difference that can be seen from this figure 7 and plots given by analytical models is that the reemission coefficient N depends very weakly on the absorbed flux and on time approximately at $t^{1/2}$. This gives N values a factor of 2-3 times smaller than the Similarity Model. Experiments have shown that the scaling laws described by Murakami are in better agreement with x-ray confinement tests performed in the laboratory, although improved opacity calculations are desired (Murakami, 1991). Another trend that is evident is that the reemission coefficient increases with incoming flux, which would suggest a smaller surface area reflectors would be desirable. For instance, in the case of absorbed flux of 10^{13} W/cm^2, the x-rays would make reemitted roughly ten times before being lost.

There are certain limitations to using a Hohlraum like cavity. The design and analysis assumes a constant input flux and radiation spectrum, which will not be the case during the collapse of the pinch. Furthermore, it can be seen from both models that the reemission coefficient increases with the incoming wall flux, which would suggest the use of small confinement cavities. Although the ablation material depth is typically on the order of microns, for longer missions (months – years) this can add up over hundreds of thousands of pulses spanning over an extended operating period. Cooling of the Hohlraum material would only decrease its performance, as it would decrease the plasma intensity inside the wall and limit the number of reemissions. Because of these shortcomings, the use of multilayer materials needs to be investigated, as well as the cooling techniques necessary for its proper use. Additionally, a simple analytical analysis will show that multilayer structures have superior reflectivities than that of gold alone.

MULTILAYER REFLECTORS

Broad-band optics for x-rays have traditionally consisted of high Z, high density, single element thin-films (e.g. gold), reflecting in grazing incidence by total reflection (Joenson, 1997). A promising alternative is the "super-mirror multilayer structure", in which the layer spacing has gradually been gradually decreased as a function of depth. Lead, Tungsten, and numerous carbides are the materials that are have been tested for these structures. The lower energy x-rays will be totally reflected from the surface layer, while the harder x-rays will penetrate into the multilayer until a region is reached where the layer spacing are such that the x-ray is reflected. To illustrate the advantages of multilayers over single film reflectors, a comparison has been done measuring the 20 – 95 reflectivity of an Au-coated reflector and a 600 element bi-layer W/Si supermirror by Joenson. .

In comparing the measured reflectivities of the supermirror and the gold coating, the ability of the supermirror to reflect at higher energies is clearly seen. For angles of 4.5 and 3.0 mrad, the cut off of the W/Si multilayer is determined by the absorption at 69.5 keV. At 1.5 mrad, the absorption edge is seen to have little effect and one may therefore expect considerable reflectivity (~ 200 keV) at this angle. The major limitation of the supermirror, i.e. a reflectivity far from unity, is also clearly illustrated by the measurements. This is especially severe for the higher angles but at 2 mrad and below, a reflectivity above 30% is obtained in the whole band. This is the performance cutoff for the W/Si super- mirror performance. In order to overcome this problem, other material combinations could be used in the mirror, and are being investigated, such as W/SiC (Windt, 2004).

CONCLUSIONS

For a 500 kN, 2000 Isp dense plasma focus propulsion device the energy and power flux are 1.23 x 10^5 J/cm^2 and 1.26 x 10^6 W/cm^2. The flux to the wall depends on the exposed area of the reflector, although it has been shown that it would be advantageous to have a small single element reflector. This is because the reemission increases with flux in the case of a gold film reflector, and in the case of multilayers, maximum reflectivity occurs at small angles. Additionally, a small reflector would greatly decrease cooling needs. The use of gold film, Hohlraum like cavities has been explored and for an incident flux of 10^{12} W/cm^2, the radiation will be reemitted approximately 10 times before being lost, according to the numerical work done my Murakami. In the case of multilayer structures, x-ray energies of DPF have not yet been investigated, although the trend is moving in that direction. Despite the advantages of multilayer structures over single element layers such as a greater energy band of reflectance, they would not be able to handle the incoming energy flux levels characteristic of the p-^{11}B pinch, and it is unclear whether low Z materials or cooling methods could aid. This is due in part to the lack of theory and experiment in cooling methods in DPF like environments. A 50% reflection rate was assumed in the prior DPF study which seems out of reach of current multilayer capabilities, but in the reach of single film Hohlraum cavities. An investigation of inverse-Bremsstrahlung is necessary; if there are 10 passes of photons before being lost, it is very possible that it will be reabsorbed in the pinch region.

NOMENCLATURE

E_{br} = Bremsstrahlung Energy (J)
kT_e = electron temperature (keV)
M = atomic mass number
n = number of evaporated atoms
n_e = electron density (m^{-3})
P = Pressure (Torr)
P_{br} = Bremsstrahlung Power Density (W/cm^3)
P_{tot} = Total Bremsstrahlung Power Density (W/cm^3)
S_a = Absorbed Flux
S_i = Incident Flux (W/cm^2)
S_r = Reflected Flux (W/cm^2)
S_s = Source Flux (W/cm^2)
t = time (s)
T = Temperature (K)
V_{pin} = Pinch Volume (m^3)
Z_{eff} = Effective Atomic Number
τ_p = Pinch Lifetime (s)
ν = Repetition Rate (Hz)

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